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FILLER METAL STRENGTHS IN BRAZED COPPER JOINTS

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A Report of an Investigation Conducted by

THE ENGINEERING EXPERIMENT STATION OF THE UNIVERSITY OF ILLINOIS

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I. INTRODUCTION

1. Object and Scope of the Investigation:

The objective of this study is to determine the strength, at various temperatures, of brazed joints in copper joined with various brazing materials.

The strength of a brazed joint depends on a number of factors. Some of these factors are as follows:[1]

A. The strength of the materials being joined. Generally speaking, the strength of the materials joined will determine the strength of a brazed joint.

B. The strength of the filler metal. The strength which can be developed in a brazing filler metal varies somewhat with the strength of the members joined. This study of the filler metal strength in brazed copper joints concerns base metals and filler metals whose room temperature tensile strengths are essentially the same -- slightly greater than 30,000 psi.

C. The thickness of the filler metal layer. In general a thin layer will provide the strongest joint.

D. The manner in which the filler metal adheres to, or coalesces with, the members joined. Ordinarily the filler metal and brazing technique selected are such that actual alloying takes place with the formation of a strong interfacial layer. However, a weak brittle layer at the interface may, under certain conditions, reduce the strength of a brazed joint.

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1. Welding Handbook, American Welding Society, Third Edition, 1950, pp. 864-865.

E. The magnitude of flux inclusions or voids in a joint. Obviously the strongest joints are those in which the bond extends over the entire joint area, uninterrupted by voids or foreign matter of any kind.

F. The manner in which the load is applied to a joint. The strongest joints are generally those in which the entire joint area is uniformly loaded. If one part of the joint carries a greater part of the load, that part may fail first and then the entire joint may fail by a progressive tearing action.

While this investigation has been concerned with a number of factors, the emphasis has been placed on the strength of the filler metals. Very little information is available concerning the expected strengths of filler metals in brazed copper joints. A joint designed according to present practice, a lap length equal to three times the least thickness of the materials joined, and properly brazed, would most assuredly fail in the base metal. Therefore, no indication of the actual filler metal strength would be obtained from a joint so designed. To obtain the desired information it was necessary to design a joint or select a length of lap such that the failure would always occur in the joint itself and thus give an indication of the actual filler metal strength.

In order to reduce the variables in this program to a minimum and to select the most suitable types of specimens, several groups of preliminary tests were conducted before the start of the major testing program.

In the main program the tests were conducted on two types of copper and six representative types of brazing materials. The two types of base metals were, Electrolytic Tough-Pitch Copper and Deoxidized

High-Phosphorus Copper; the brazing materials used were BAg-1, BAg-6, BAg-8, BCuP-4, BCuP-2, and BCuP-5.* These materials were tested in double and single lap-joints both with and without fillets, and in butt-type joints. The details of the joints are shown in Fig. 1.

Although the major part of the investigation was conducted at room temperature a number of tests were also run at +400° F. and -321° F. These tests were conducted to establish the general relationship of the joint strengths at high and low temperature to the room temperature strengths.

2. Acknowledgements:

The tests described in this report were a part of an investigation resulting from a cooperative agreement between the Engineering Experiment Station of the University of Illinois and the Copper and Brass Research Association.

This work was done as a part of the structural research program of the Department of Civil Engineering under the general direction of N. M. Newmark, Research Professor of Structural Engineering. The study was conducted by D. C. Crawford, Research Assistant in Civil Engineering, under the immediate supervision of W. H. Munse, Research Associate Professor of Civil Engineering. The specimens were prepared by Laboratory Mechanics E. R. Reimer, G. E. Rymer, and E. R. Kirby, while W. McKenzie, a Senior Laboratory Attendant, assisted with the testing.

The specimens and scope of the program were planned with the assistance of an Advisory Committee consisting of the following persons.

* Tentative Specifications for "Brazing Filler Metal," ASTM Designation: B260 - 52T, 1952.

Arthur N. Kugler, Chairman	B. A. Hackett
L. W. Hawthorne, Vice-Chairman	Robert J. Metzler
A. I. Heim, Secretary	N. M. Newmark
A. Stanley Cross, Jr.	T. E. Velfort
S. A. Greenburg	J. J. Vreeland

The assistance and advice of this group is gratefully acknowledged.

II. PRELIMINARY TESTS

3. Tests of Lap Joints

Several groups of preliminary specimens were fabricated and tested before the start of the major testing program. This preliminary work provided a basis for the selection of the type of specimen to be used, and the amount of lap necessary to insure that the failures occur in the joints. The tests were also used to develop a fabrication procedure from which sound brazed joints could be obtained.

a. Group I - The first group of preliminary specimens were prepared in an industrial laboratory and shipped to the University for the purpose of determining the length of lap necessary to study the shearing strength of the filler metal. Sixteen 1-in. wide lap-joints of 1/4-in. thick copper were included: eight of electrolytic copper and eight of deoxidized copper. Shims were used to control the thickness of the filler metal layer. The joints were reduced to a width of 1/2-in. at the lap; and the lap lengths were machined to 1/4, 3/16, 1/8, and 1/16 in. Joints of each lap length were then tested in pairs as double lap-joint specimens.

The results of the first group of preliminary tests were very inconsistent. From these tests it was concluded that the brazing technique was not satisfactory. The results also demonstrated that if the joint was reasonably void of porosity the lap should not be over 3/16-in. to insure failure in the joint.

b. Group II - The second group of preliminary tests consisted of ten specimens of the type shown in Fig. 2. The purpose of these tests was to determine if more consistent results could be obtained by using a specimen in which the loading was symmetricial. The length of lap was varied from 1/8 in. to 5/8 in. Very inconsistent results were obtained in these tests also. It was concluded that the specimen shown in Fig. 2 would not be satisfactory because there was little control over the filler metal thickness. The copper expanded during heating and produced large variations in the gap between the pieces being joined.

c. Group III - The third group of specimens were brazed by procedures developed with the assistance of Mr. H. A. Huff a brazing specialist of Air Reduction Co. The purpose of Mr. Huff's visit was to assist the laboratory personnel in developing a suitable procedure for the brazing of sound joints. The visit resulted in the development of procedures by which sound joints could be prepared.

The specimens of the third group were lap joints of both types of copper. Several different methods of controlling the filler metal thickness were tried; some joints were pre-tinned, and others were brazed with shims as spacers. The brazing was done by both Mr. Huff and the laboratory personnel.

As soon as the specimens cooled they were reduced to a lap length of approximately 3/16 in. in the joint and tested. The test results were much more consistent than the previous results. The ultimate strengths, based on a 3/16 in. lap, averaged approximately 20,000 psi. for the joints brazed by both men. Thus it was found that the laboratory brazer was qualified to make sound and consistent joints. The project personnel were now in posession of a specimen fabrication technique and procedure whereby consistently good joints could be obtained.

d. Group IV - The fourth group of preliminary specimens were brazed and tested to determine the consistency of joints prepared by the procedure developed in the third group of tests. Twenty four joints were prepared utilizing both base metals and all the filler metals. The joints were tested in two groups: single lap-joints with fillets and lap-joints without fillets. The lap lengths for all joints were set carefully at 3/16 in. before brazing. However, because of the expansion of the copper during heating, the actual lap lengths were in excess of 3/16 in.

All joints were of good quality but demonstrated a distinct difference in the type of failure in the two types of copper. The joints of electrolytic copper failed in the brittle copper oxide adjacent to the braze interface while the joints of deoxidized copper failed in the base metal away from the joint. In all cases the loads carried by the deoxidized copper specimens were greater than those carried by the electrolytic copper specimens. From the results of these tests it was evident that the lap must be less than 3/16 - in. before brazing to insure failure in the filler metal of deoxidized copper joints.

e. Group V - A fifth group of specimens was prepared with a reduced lap length. Tempilstiks were used as a means of determining the approximate maximum temperature reached during brazing. Six electrolytic and six deoxidized joints were tested without fillets. The laps were set at approximately 0.17 in. before brazing. After brazing the lap length averaged 0.20 in.

All deoxidized-copper joints failed in the base metal; the electrolytic-copper specimens failed in the joint with an approximate strength of 17,000 psi. Thus, a still shorter lap is required for joint failure in deoxidized copper. The Tempilstiks were found to be extremely helpful in indicating when a joint had been overheated.

f. Group VI - The purpose of the sixth group of preliminary specimens was to determine if a lap of 0.15-in. in the deoxidized copper joints was short enough to provide a filler metal failure. Three double lap-joint specimens of deoxidized copper were prepared: one joint was brazed with a single-tip torch and the second joint with a double-tip torch. The joints failed in the filler metal with an average strength of slightly less than 20,000 psi. There was no difference in the strengths of the joint brazed with the two different torches. The results show also that a lap of 0.15-in. is small enough to provide failures in the filler metal. The dual-tip torch was found to be easier to handle, provided a more uniform heat and reduced the brazing time.

4. Tests of Butt Joints

a. Group VII - The seventh group of preliminary specimens was a complete series of butt joints. The brazing procedure used on these specimens consisted of preheating the copper to the brazing temperature in order to set the gap at 0.003-in., clamping both ends of the joint in this position, and then brazing. The test results from these joints were quite inconsistent. Consequently it was decided that further studies should be made to improve the brazing procedure.

b. Group VIII - The last group of preliminary specimens were brazed butt joints also. Four deoxidized and four electrolytic specimens were prepared. The brazing procedure was quite different from that used previously. One end of the specimen was clamped, the other end was placed in line and against it and allowed to remain free. This free end was permitted to expand without restraint as the two ends were brazed. The results of this group of tests were very consistent, the average strength of the joints being approximately 26,000 psi. On the basis of these results, it was decided to use this latter brazing procedure for the butt joints in the major program.

III. DESCRIPTION OF SPECIMENS AND TESTS

5. Materials Used in Specimen Fabrication

The copper used for specimen fabrication was certified to conform to ASTM Specification B152 and reported to have the following physical and chemical properties:

Electrolytic copper:

Copper content: 99.942 percent

Tensile strength: 31,500 psi

Elongation in 2 in.: 50 percent

Deoxidized High-Phosphorus copper:

Copper content: 99.942 percent

Tensile strength: 31,600 psi

Elongation in 2 in.: 45 percent

Phosphorus content: 0.029 percent

The brazing materials used in the fabrication were received from three different suppliers: Materials BAg-1 and BAg-8 from the first supplier, BAg-6 and BCuP-5 from the second, and BCuP-4 and BCuP-2 from the third. All of these filler metals were in wire form, 1/16 in. in diameter. The flux, required for use with the filler metals of the first two suppliers, was a paste. No flux was required for the remaining filler metals. Table 1 gives the chemical and physical properties of each of the filler metals.

Brazing filler metals of the BCuP classifications are used primarily for joining copper and copper alloys, and are suitable for all brazing processes. These filler metals have self-fluxing properties when used on copper.

It will be noted in Table 1 that the brazing temperature-ranges begin below the liquids temperature. It is generally recommended that the lower temperatures within the recommended ranges be used in brazing. However, the required temperature may vary somewhat with the joint clearance and the time needed to complete the braze.

BCuP-2 filler metal is extremely fluid at brazing temperatures and will penetrate joints with very little clearance. Best results are obtained with clearances of 0.001 to 0.003 in.

Filler metals of the BAg classifications may be used for joining all ferrous and non-ferrous metals except aluminum, magnesium, titanium, and other metals melting below 1500° F. They are used with all brazing processes and are generally rapid-melting and free-flowing. Lap-type joints are recommended but butt-type joints may be used if strength requirements are less stringent. Clearances should be between 0.002 and 0.005 in. for proper capillary attraction. A flux is generally required.

BAg-1 brazing filler metal is free-flowing and also has other qualities making it well suited for general-purpose work. Its melting range is very narrow.

BAg-6 filler metal is used particularly for brazing in the electrical industry. It is also used in the dairy and food industries where the use of cadmium-containing alloys might be prohibited.

BAg-8 filler metal is used primarily in the assembling of electronic and vacuum tubes. The metal is generally free flowing.[2]

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2. ASTM Standards 1952, Part 2, Non-Ferrous Metals, Specifications for Brazing Filler Metal (B260-52T), pp. 508-509.

6. Specimen Designation

The specimens tested have been numbered in a manner which will indicate the type of specimen or joint, the type of copper, the type of filler metal, the testing temperature, and distinguish between duplicate specimens. In order to obtain a designation system that will provide this data, each specimen has been numbered in accordance with the following system.

First Symbol: The first number indicates the type of joint or specimen.

1. Double lap-joints, fillets removed.
2. Double lap-joints, fillets not removed.
3. Single lap-joints, fillets removed.
4. Single lap-joints, fillets not removed.
5. Butt-Joints.

Second Symbol: The first letter indicates the type of copper.

E. Electrolytic tough-pitch

D. Deoxidized High Phosphorus

Third Symbol: The second number indicates the type of filler metal.

1. BAg-1
2. BAg-8
3. BAg-6
4. BCuP-5
5. BCuP-4
6. BCuP-2

Fourth Symbol: The second letter indicates the temperature at which the specimens were tested.

A. +400 F. (1st group)

B. +400 F. (2nd group)

C. Room temperature (approx. 70 F.)

D. -321 F. (1st group)

E. -321 F. (2nd group)

R. Duplicate room temperature specimens

Fifth Symbol: The third number (preceded by a dash) distinguishes between duplicate specimens.

Either 1 or 2.

Sixth Symbol: The third letter (used in double specimens only for data recording) distinguishes between the two joints in a double specimen.

Either A or B.

7. Specimen Preparation

(a) Lap Joints. - Copper sheets 1/4 in. thick, approximately 30 in. long and 6 in. wide were shipped to the laboratory for these tests. Strips approximately 7/8 in. wide and 6 in. long were cut from these sheets. Since the sheets were sheared to a width of 6-in., all cuts for the strips were made across the width of the sheet. Approximately 3/8 in. was then cut from one end of each strip (the end to be brazed) to eliminate the taper in thickness which existed at the ends of the strips. This cut end and one long edge were next machined square with the surface of the strips to insure the desired alignment of the strips when they were placed in the brazing jig. Before brazing, approximately one inch of the face of each strip, at the end to be joined, was lightly filed to remove the oxidized surface as well as any foreign matter which may have been present on the surface of the copper. The filed area was next rubbed lightly with a 2/0 emery cloth and wiped clean with carbon-tetrachloride to insure the removal of all oil, grease or dirt. The copper was then ready to be brazed.

The appropriate flux, when required, was brushed on the filed areas of the strips to be joined. The strips were then placed in the brazing jig as shown in Fig. 3. The strips were next clamped with a lap length of 0.15 in. for the joints to be tested with fillets. A 0.003 in. feeler gage was used in setting the joint clearance or gap. At times, a great deal of difficulty was encountered in setting the gap at 0.003 in. The fact that the parent copper sheets were not perfectly flat occasionally made it necessary to introduce additional clamps or to slightly bend the strips to bring them into the desired position.

The next operation was the actual brazing. The average brazing time was 16 seconds for the lap joints. However, the time for each individual joint depended, to some extent, upon the liquidus temperature of the brazing material. As soon as the torch was removed, the clamp on the upper strip (right end of the specimen in Fig. 3) was loosened to prevent the development of residual stresses in the joint with the cooling of the copper. At the same time, Tempilstiks, representing the maximum and minimum limits of the specified brazing temperature range, were touched to the joint directly above the lap. This was done to determine if the temperature of the joint was within the brazing temperature range. Overheating occured in a few of the joints and in these cases it was found that the brazing time was always greater than 20 seconds. The slight overheating, however, did not appear to have any pronounced affect upon the strength of the joints.

Final machining consisted of reducing the width of the gage section of the joint to 1/2 in. The fillets were then removed from the joints of series 1 and 3 and the laps reduced to 0.15 in. by machining.

The length of the lap of each joint was measured with a device utilizing a microscope eye-piece and a dial indicator which read to ten-thousandths-of an inch. This apparatus is shown in Fig. 4. The width of the lap was measured with a micrometer.

The last step in the specimen fabrication procedure was the brazing of two joints to form the double specimens. The lap joints were immersed in water to prevent the brazes from being re-heated while the specimens were joined at the end. This joining of the specimens helped to distribute equally the applied load to the two joints.

(b) Butt Joints. - The preparation of the butt joints followed the same general procedure as the lap joints through the initial machining. The ends to be joined were then filed, rubbed with emery cloth, and wiped clean with carbon-tetrachloride.

The appropriate flux was then brushed on the ends to be joined and one strip was clamped in the brazing jig. The other strip was butted in line against the clamped strip and allowed to remain loose. As previously explained, this was necessary because of the expansion of the copper during heating and the difficulty of pre-setting a gap.

The specimen was then ready to be brazed. The average brazing time for butt joints was 12 seconds, slightly less than the time required to braze a lap joint.

Before testing, the excess filler metal was removed from the faces and edges of the joint and the width and thickness were then measured with a micrometer.

8. Brazing Procedure

The brazing procedures were fundamentally the same for both the lap and butt joints. A medium-light weight torch with 5 hole (68 drill) dual tips was used for brazing. By means of a 2-stage regulator, constant oxygen and acetylene pressures were used throughout the brazing operations: oxygen, 20 psi. and acetylene, 2.5 psi.

The strips were heated for a distance of approximately 2 in. on each side of the joint by playing the torch flames directly on the metal. First the strip on one side was heated and then the strip on the other side. This heating was accomplished by short, rapid lateral motions of the torch. The operator changed sides approximately every two seconds as he worked the maximum heat to the center of the joint. No vertical motion of the torch was necessary when the dual tips were set approximately 1 1/2 in. apart.

When the operator thought the temperature at the joint was within the brazing range he touched the filler metal to the specimen at the joint, the torch being moved to one side so as not to place the flame directly on the filler metal. If the filler metal flowed immediately upon touching the base metal, the torch was removed and extinguished; the brazing process being completed. If the filler metal failed to flow, it was removed and additional heat was applied to the joint and the same process repeated until proper flow was obtained. Seldom did this process have to be repeated over once.

9. Description of Tests

(a) Room Temperature. - One hundred-twenty specimens were tested at room temperature. A series of tests (all possible combinations of copper and filler metals, duplicated) were run on each of the five types of joints.

The specimens were tested in a 120,000 lb. hydraulic testing machine. The lap-joint tests were conducted in the same manner as a standard tension test with a few slight exceptions. For testing double specimens a 1/2 in. spacer bar which can be seen in Fig. 5, was introduced between the two strips at the end of the specimen. The spacer bar enabled the specimen to be gripped tightly in the upper jaw of the testing machine as shown in Fig. 7.

The jaws in the pull heads of the testing machine were offset 1/8 in. in opposite directions for the tests of single lap-joint specimens. These offsets placed the pressure line of pull directly through the braze.

Slip gages were designed for both the double and single specimens and are shown in Figs. 5 and 6. The purpose of these dials was to obtain a measure of the slip or deformation in the joint during loading and to provide a basis of comparison of the different types of materials and joints. The mountings were designed so that the elongation of the copper did not, in general, effect the slip readings. The deformation in the lap joints was recorded at 100 lb. increments throughout each of the tests.

The butt joints were tested in the same manner as a standard tension test. Load-elongation readings were taken on a few of the specimens and the curves obtained were so nearly identical that it was considered to be unnecessary throughout the balance of the series.

(b) Tests at +400° F. - Twelve single lap-joints without fillets were tested at +400° F. Deoxidized copper and three filler metals were used: BAg-1, BCuP-2, and BCuP-5. Thus, there were three groups of four identical specimens.

The specimens were placed in the special pull-head assembly as shown in Fig. 8. The assembly was then placed inside a furnace and the entire assembly placed in a 60,000 lb. Riele Universal testing machine as shown in Fig. 9. A thermocouple was attached to the specimen at the lap, and the pull head assembly connected to the heads of the machine.

A Speed-O-Max recorder, shown in Fig. 9, was used to record the temperature of the joint. This recorder was standardized using a portable potentiometer.

The heating process was then begun. Voltage input into the furnace was controlled by the use of a variable voltage transformer. The maximum voltage, 120 to 125 volts, was switched into the furnace and allowed to remain on until the temperature of the specimen reached +396° F. Then the voltage was cut to 50 volts and the temperature allowed to stabilize at +400° F. before testing. The average total time elapsed from the start of heating to the completion of the test was 1 hour 25 minutes.

Time vs. temperature records made by the recorder revealed a very near straight line relationship at maximum voltage. A typical record of the specimen temperature is shown in Fig. 11.

A preliminary heating trial was run prior to the actual specimen testing to determine the temperature at the center of the specimen and 2 in. above and below the lap. Results showed only a slight temperature differential. When the temperature at the lap had been stabilized at $+400^{\circ}$ F., the temperature 2 in. above the lap was $+401^{\circ}$ F. and 2 in. below the lap, $+395^{\circ}$ F. These temperature readings were obtained by the use of three thermocouples which could be switched alternately to record the temperature.

(c) Tests at -321° F. - Twenty-four single lap joints without fillets were tested at -321° F. Deoxidized copper and six filler metals were used. Thus, there were six groups of four identical specimens. The specimen for the low temperature tests was placed in the special pull head assembly used for the tests at $+400^{\circ}$ F. The assembly was then placed in a closely fitting container which was open at the top. The container, in turn, was placed in the large insulating tank shown in Fig. 10.

Liquid nitrogen was forced into the open container which held the specimen and pull heads. The container was filled to the top, a level which completely covered the upper pull head of the test assembly. After the level of the liquid nitrogen had been maintained at the top of the container for 10 to 15 minutes, the boiling of the liquid nitrogen diminished to a negligible amount which gave assurance that all parts which were in the bath had been lowered to a temperature of -321° F. The load was then applied to the test specimen.

IV. ANALYSIS AND DISCUSSION OF TEST RESULTS

10. Results of Tests

(a) Room temperature tests. - The results of the room temperature tests are summarized in Tables 2 to 6 inclusive. In general, the ultimate strengths obtained for each type of joint were quite consistent. The stress-slip relationships for the lap joints were also consistent with regard to the joint type as shown in Figs. 12 and 13.

Overall averages of the filler metal strength in the five types of joints tested are as follows:

1.	Double lap-joints without fillets:	18,200 psi.
2.	Double lap-joints with fillets:	23,300 psi.
3.	Single lap-joints without fillets:	18,600 psi.
4.	Single lap-joints with fillets:	23,100 psi.
5.	Butt joints:	26,500 psi.

(b) Tests at +400° F. - The results of tests at +400° F. are shown in Table 7. These results show that the average strengths of the three filler metals tested are slightly in excess of 10,000 psi. at +400° F. This is a reduction in strength of approximately 44 percent from the room temperature strength of the same joint. The reduction in strength of deoxidized copper coupons tested at the same temperatures has been found to be approximately 24 percent.[3] Thus, the elevated temperature has a greater affect on the filler metal strength than it does on the copper itself.

(c) Tests at -321° F. - The results of tests at -321° F. are shown in Table 8. The average strengths of the six filler metals were in no manner consistent. However, when the brazes were sound, a marked

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3. "Mechanical Properties of Copper at Various Temperatures," by W. H. Munse and N. A. Weil, presented at the Fifty-fourth Annual Meeting of the ASTM,

degree of consistency was found to exist between the four specimens tested of each filler metal. The average filler metal strengths ranged from 30,100 psi for BAg-1, 158 percent of the room temperature strength, to 17,900 psi for BCuP-2, 96 percent of the room temperature strength. Based on coupon tests[4], the strength of deoxidized copper at this temperature is approximately 165 percent of the room temperature strength. Thus, the low temperature has a lesser affect on the strength of the filler metal than it does on the copper itself.

11. Effect of the Type of Copper

The average strengths of lap joints of both types of copper were found to be approximately the same while the strengths developed in the butt joints were generally stronger in specimens of deoxidized copper than in electrolytic copper. The overall averages were as follows:

	Deoxidized	Electrolytic
1. Double lap-joints without fillets:	18,100 psi	18,400 psi
2. Double lap-joints with fillets:	23,500	23,000
3. Single lap-joints without fillets:	18,300	18,800
4. Single lap-joints with fillets:	22,600	23,700
5. Butt joints:	28,000	24,900

A definite characteristic type failure was observed for joints of each type of copper. In the deoxidized copper joints the failure almost always occured in the filler metal while in the electrolytic copper joints the failure almost always occured near the interfacial layer along one of the first grain boundaries in the copper parallel to the filler metal layer, as shown in Fig. 14.

4. "Mechanical Properties of Copper at Various Temperatures," by W. H. Munse and N. A. Weil, presented at the Fifty-fourth Annual Meeting of the ASTM, June 1951.

12. Effect of Joint Type and Fillets

It can be seen in Fig. 15 that the average ultimate strengths of the single and double specimens were approximately equal for joints with fillets and for joints without fillets. This indicates that the specimen type had no significant affect on the ultimate joint strength. However, the joints with fillets were considerably stronger than the joints without fillets.

It should be pointed out that the greater ultimate strength exhibited by joints tested with fillets is in reality fictitious because the area of the fillets has not been taken into account in the determination of the ultimate stress. In other words, considering two joints with the same lap, one with and the other without fillets, the joint with fillets can be expected to carry a maximum load which will average 20 to 30 percent greater than that which would be carried by the joint if the fillets were removed. This, of course, is true only for the very small lap areas used in this study.

The manner in which the joints were loaded undoubtedly had some affect on the joint strength. A bending moment was created on the joints because a lap joint is not loaded symmetrically. This moment produced tensile stresses in the filler metal which were highest at the ends of the joints. Since failure started at the highly stressed ends of the joints and proceeded by a progressive tearing action it is likely that this complex state of stress had an effect on the strength of the filler metal.

13. Effect of the Type of Filler Metal

In Fig. 16 a comparison is made of the ultimate strength and type of filler metal for the various types of joints. Very little variation in ultimate strength with filler metal was found for single and double specimens without fillets, although specimens brazed with BCuP-2 appeared to be the strongest of the specimens tested.

An appreciable variation was found to exist in the ultimate strengths of double and single specimens with fillets. As shown in Fig. 16, the variation seems to be similar for both the single and double specimens. This variation is best described in terms of the percent of strength increase over joints without fillets. These average increases for the various filler metals are: BAg-1, 34 percent; BAg-8, 21 percent; BAg-6, 37 percent; BCuP-5, 20 percent; BCuP-4, 33 percent; and BCuP-2, 14 percent. The variation of strength increase indicates that the fillet size and thus the ultimate strength may be dependent on the filler metal used.

14. The Effect of Heating Time and Liquidus Temperature

As previously stated, the characteristic type of failure in the electrolytic copper joints was in the base metal near the interfacial layer where a brittle copper oxide product was formed. Because this formation is caused by the heating it is logical to assume that the joint strength should decrease as the required time to braze the joint increases. Since the required brazing time (if the procedure is maintained constant) is directly proportional to the liquidus temperature of the filler metal, the joint strength obtained for electrolytic copper may be inversely proportional to the required brazing time and thus, the liquidus temperature of the filler metal. Fig. 17 demonstrates the veracity of the above statement.

The figure shows four comparative relationships for each of the six filler metals: Liquidus temperatures, average brazing times for all electrolytic lap joints, ultimate strengths for the double electrolytic lap joints without fillets, and the ultimate strengths of electrolytic butt joints. Each brazing time plotted is the average of 12 brazes. This gives a better indication of the actual average times than taking only the average times for the double joints without fillets. The ultimate strengths plotted for the electrolytic lap-joints without fillets are the average of the two double specimens or four joints so it can be assumed that the values are of reasonable worth in this type of analysis. The ultimate strength values for the butt joints are the average of duplicate specimens and can be expected to have a greater variation than those for the lap joints. While the butt joints require a shorter heating time than the lap joints it was thought that if their strength values followed the same trend as those for the lap joints, it would further verify these conclusions. Fig. 17 clearly illustrates that the strengths generally vary inversely with brazing time and liquidus temperature.

15. Effect of Testing Temperature

Elevated and low temperatures have a marked effect on the strength of the filler metal in deoxidized copper joints. Joints tested at $+400^{\circ}$ F. experienced a reduction in strength of approximately 44 percent based on the room temperature strength of the same type of joint. The differences in strength of the three filler metals tested at +400° F. are small and it is impossible to make a conclusive statement as to which is the strongest. The ultimate strengths of joints prepared with BCuP-2 and BCuP-5 filler metals were very nearly the same and slightly greater than those prepared with BAg-1 filler metal.

The filler metals in the specimens tested at -321° F. displayed a marked variation in strength. It is immediately evident that silver alloys have a greater strength at low temperatures than the copper-phosphorus alloys. There seems to be an inverse relationship between strength and the percent of the major constituent in the filler metal. This relationship is shown in Fig. 18.

V. SUMMARY

1. Summary of Test Results

The significant results of the tests are summarized as follows:

(a) The strength of lap-joints for both types of copper were approximately the same. Butt joints of deoxidized copper were slightly stronger than those of electrolytic copper.

(b) Room temperature strengths for all filler metals in both single and double lap-joints without fillets were approximately the same and averaged slightly greater than 18,000 psi.

(c) Room temperature strengths for each filler metal in both single and double lap-joints with fillets were approximately the same and ranged from 21,000 psi to 26,000 psi for the various filler metals.

(d) Specimens with fillets experienced a greater deformation before failure than those without fillets.

(e) Joint strengths for specimens tested at +400° F. averaged approximately 10,000 psi.

(f) Joint strengths for specimens tested at -321° F. ranged from 158 percent of the room temperature strength to 96 percent of the room temperature strength.

2. Conclusions

The following conclusions are based on the results of the tests:

(a) With proper fabrication procedures, consistently strong joints can be obtained.

(b) Although the type of failure was different for the two types of copper, the room temperature lap-joint strengths were, for all practical purposes, the same.

(c) The presence of fillets on a joint contributed to a considerable strength increase. The average increase in strength for the joints tested depends on the filler metal used.

(d) In general, the strength of joints of electrolytic copper decreased as the liquidus temperature of the filler metal and the brazing time increased.

(e) A temperature of +400° F. had a greater effect on the filler metal strength than it did on the copper itself.

(f) A temperature of -321° F. had a lesser effect on the filler metal strength than it did on the copper itself.

(g) The BAg- filler metals are stronger at -321° F. than the BCuP- filler metals.

TABLE 1

SUMMARY OF FILLER METAL PROPERTIES

Series No.	AWS-ASTM Designation	Chemical Composition (percent)					Solidus (Temp. °F.)	Liquidus (Temp. °F.)	Brazing Temp. Range, °F.
		Cu	Ag	Zn	Cd	P			
1.	BAg-1	15	45	16	24		1125	1145	1145-1400
2.	BAg-8	28	72				1435	1435	1435-1650
3.	BAg-6	34	50	16			1270	1425	1425-1600
4.	BCuP-5	80	15			5	1185	1500	1300-1500
5.	BCuP-4	87	6			7	1185	1380	1300-1500
6.	BCuP-2	93				7	1305	1485	1350-1550

TABLE 2

SUMMARY OF TEST RESULTS - DEOXIDIZED COPPER - DOUBLE LAP-JOINT SPECIMENS

Spec. No.	Fillet	Filler Metal		Ult. Strength psi
1D1C-1	Without	BAg-1		16250
1D1C-2	Without	BAg-1		17770
			Av.	17010
1D2C-1	Without	BAg-8		20160
1D2C-2	Without	BAg-8		17410
			Av.	18790
1D3C-1	Without	BAg-6		18520
1D3C-2	Without	BAg-6		15770
			Av.	17150
1D4C-1	Without	BCuP-5		17720
1D4C-2	Without	BCuP-5		20330
			Av.	19030
1D5C-1	Without	BCuP-4		15600
1D5C-2	Without	BCuP-4		20430
			Av.	18020
1D6C-1	Without	BCuP-2		15220
1D6C-2	Without	BCuP-2		21970
			Av.	18600
2D1C-1	With	BAg-1		22570
2D1C-2	With	BAg-1		22500
			Av.	22540
2D2C-1	With	BAg-8		20020
2D2C-2	With	BAg-8		24030
			Av.	22030
2D3C-1	With	BAg-6		22390
2D3C-2	With	BAg-6		24720
			Av.	23560
2D4C-1	With	BCuP-5		22420
2D4C-2	With	BCuP-5		22440
			Av.	22430
2D5C-1	With	BCuP-4		22090
2D5C-2	With	BCuP-4		28000
			Av.	25050
2D6C-1	With	BCuP-2		25620
2D6C-2	With	BCuP-2		25470
			Av.	25550

TABLE 3

SUMMARY OF TESTS RESULTS - ELECTROLYTIC COPPER - DOUBLE LAP-JOINT SPECIMENS

Spec. No.	Fillet	Filler Metal		Ult. Strength psi
1E1C-1	Without	BAg-1		19300
1E1C-2	Without	BAg-1		16610
			Av.	17960
1E2C-1	Without	BAg-8		16930
1E2C-2	Without	BAg-8		18510
			Av.	17720
1E3C-1	Without	BAg-6		17840
1E3C-2	Without	BAg-6		20170
			Av.	19000
1E4C-1	Without	BCuP-5		15710
1E4C-2	Without	BCuP-5		19510
			Av.	17610
1E5C-1	Without	BCuP-4		19850
1E5C-2	Without	BCuP-4		18300
			Av.	19080
1E6C-1	Without	BCuP-2		20010
1E6C-2	Without	BCuP-2		17960
			Av.	18970
2E1C-1	With	BAg-1		23590
2E1C-2	With	BAg-1		24650
			Av.	24120
2E2C-1	With	BAg-8		19170
2E2C-2	With	BAg-8		23560
			Av.	21370
2E3C-1	With	BAg-6		30110
2E3C-2	With	BAg-6		25960
			Av.	28040
2E4C-1	With	BCuP-5		18030
2E4C-2	With	BCuP-5		20940
			Av.	19490
2E5C-1	With	BCuP-4		24000
2E5C-2	With	BCuP-4		27800
			Av.	25900
2E6C-1	With	BCuP-2		17900
2E6C-2	With	BCuP-2		20740
			Av.	19320

TABLE 4

SUMMARY OF TEST RESULTS - DEOXIDIZED COPPER - SINGLE LAP-JOINT SPECIMENS

Spec. No.	Fillet	Filler Metal		Ult. Strength psi
3D1C-1	Without	BAg-1		19370
3D1C-2	Without	BAg-1		18710
			Av.	19040
3D2C-1	Without	BAg-8		18660
3D2C-2	Without	BAg-8		16670
			Av.	17620
3D3C-1	Without	BAg-6		16290
3D3C-2	Without	BAg-6		18930
			Av.	17610
3D4C-1	Without	BCuP-5		18350
3D4C-2	Without	BCuP-5		17450
			Av.	17900
3D5C-1	Without	BCuP-4		22960
3D5C-2	Without	BCuP-4		15340
			Av.	19150
3D6C-1	Without	BCuP-2		16960
3D6C-2	Without	BCuP-2		20310
			Av.	18640
4D1C-1	With	BAg-1		23080
4D1C-2	With	BAg-1		23230
			Av.	23160
4D2C-1	With	BAg-8		25000
4D2C-2	With	BAg-8		21110
			Av.	23060
4D3C-1	With	BAg-6		23570
4D3C-2	With	BAg-6		24790
			Av.	24180
4D4C-1	With	BCuP-5		19800
4D4C-2	With	BCuP-5		19780
			Av.	19790
4D5C-1	With	BCuP-4		23450
4D5C-2	With	BCuP-4		25400
			Av.	24430
4D6C-1	With	BCuP-2		20900
4D6C-2	With	BCuP-2		16220*
			Av.	20900

*No fillets - not included in average.

TABLE 5

SUMMARY OF TEST RESULTS - ELECTROLYTIC COPPER - SINGLE LAP-JOINT SPECIMENS

Spec. No.	Fillet	Filler Metal		Ult. Strength psi
3E1C-1	Without	BAg-1		13550*
3E1C-2	Without	BAg-1		18060
			Av.	18060
3E2C-1	Without	BAg-8		19380
3E2C-2	Without	BAg-8		20110
			Av.	19750
3E3C-1	Without	BAg-6		18730
3E3C-2	Without	BAg-6		18770
			Av.	18750
3E4C-1	Without	BCuP-5		15960
3E4C-2	Without	BCuP-5		20700
			Av.	18330
3E5C-1	Without	BCuP-4		19160
3E5C-2	Without	BCuP-4		16840
			Av.	18000
3E6C-1	Without	BCuP-2		19480
3E6C-2	Without	BCuP-2		20590
			Av.	20040
4E1C-1	With	BAg-1		25100
4E1C-2	With	BAg-1		29950
			Av.	27530
4E2C-1	With	BAg-8		19830
4E2C-2	With	BAg-8		25050
			Av.	22440
4E3C-1	With	BAg-6		23890
4E3C-2	With	BAg-6		12990**
			Av.	23890
4E4C-1	With	BCuP-5		23850
4E4C-2	With	BCuP-5		23890
			Av.	23870
4E5C-1	With	BCuP-4		25310
4E5C-2	With	BCuP-4		22060
			Av.	23690
4E6C-1	With	BCuP-2		20480
4E6C-2	With	BCuP-2		19440***
			Av.	20480

* Considerable porosity - not included in average.
** Very poor bond - not included in average.
*** No fillets - not included in average.

TABLE 6

SUMMARY OF TEST RESULTS - BUTT JOINTS

Spec. No.	Copper	Filler Metal		Ult. Strength psi
6E1R-1	Elect.	BAg-1		20300
6E1R-2	Elect.	BAg-1		22300
			Av.	21300
6E2R-1	Elect.	BAg-8		22800
6E2R-2	Elect.	BAg-8		20700
			Av.	21800
6E3R-1	Elect.	BAg-6		27700
6E3R-2	Elect.	BAg-6		27700
			Av.	27700
6E4R-1	Elect.	BCuP-5		28300
6E4R-2	Elect.	BCuP-5		22700
			Av.	25500
6E5R-1	Elect.	BCuP-4		30900
6E5R-2	Elect.	BCuP-4		25200
			Av.	28100
6E6R-1	Elect.	BCuP-2		24000*
6E6R-2	Elect.	BCuP-2		25700
			Av.	24900
6D1R-1	Deox.	BAg-1		24300
6D1R-2	Deox.	BAg-1		29800
			Av.	27100
6D2R-1	Deox.	BAg-8		22900
6D2R-2	Deox.	BAg-8		27900
			Av.	25400
6D3R-1	Deox.	BAg-6		30100
6D3R-2	Deox.	BAg-6		30600
			Av.	30400
6D4R-1	Deox.	BCuP-5		26200
6D4R-2	Deox.	BCuP-5		28300
			Av.	27300
6D5R-1	Deox.	BCuP-4		25700
6D5R-2	Deox.	BCuP-4		29300
			Av.	27500
6D6R-1	Deox.	BCuP-2		31200
6D6R-2	Deox.	BCuP-2		31100
			Av.	31200

*Specimen replaced.

TABLE 7

SUMMARY OF TEST RESULTS - DEOXIDIZED COPPER - SINGLE LAP-JOINT SPECIMENS WITHOUT FILLETS - HIGH TEMPERATURE TESTS

Spec. No.	Testing Temperature	Filler Metal		Ult. Strength psi
3D1A-1	+400° F.	BAg-1		9850
3D1A-2	+400° F.	BAg-1		11400
3D1B-1	+400° F.	BAg-1		8600
3D1B-2	+400° F.	BAg-1		8900
			Av.	9700
3D4A-1	+400° F.	BCuP-5		10600
3D4A-2	+400° F.	BCuP-5		10100
3D4B-1	+400° F.	BCuP-5		12700
3D4B-2	+400° F.	BCuP-5		10000
			Av.	10850
3D6A-1	+400° F.	BCuP-2		10200
3D6A-2	+400° F.	BCuP-2		11000
3D6B-1	+400° F.	BCuP-2		11200
3D6B-2	+400° F.	BCuP-2		10400
			Av.	10700

TABLE 8

SUMMARY OF TEST RESULTS - DEOXIDIZED COPPER - SINGLE LAP-JOINT SPECIMENS WITHOUT FILLETS - LOW TEMPERATURE TESTS

Spec. No.	Testing Temperature	Filler Metal		Ult. Strength psi
3D1D-1	-321° F.	BAg-1		20100*
3D1D-2	-321° F.	BAg-1		30700
3D1E-1	-321° F.	BAg-1		31500
3D1E-2	-321° F.	BAg-1		28100
			Av.	30100
3D2D-1	-321° F.	BAg-8		21300
3D2D-2	-321° F.	BAg-8		25500
3D2E-1	-321° F.	BAg-8		12500*
3D2E-2	-321° F.	BAg-8		27400
			Av.	24700
3D3D-1	-321° F.	BAg-6		29200
3D3D-2	-321° F.	BAg-6		28500
3D3E-1	-321° F.	BAg-6		28700
3D3E-2	-321° F.	BAg-6		25700
			Av.	28000
3D4D-1	-321° F.	BCuP-5		20900
3D4D-2	-321° F.	BCuP-5		23500
3D4E-1	-321° F.	BCuP-5		21400
3D4E-2	-321° F.	BCuP-5		21900
			Av.	21900
3D5D-1	-321° F.	BCuP-4		21200
3D5D-2	-321° F.	BCuP-4		23200
3D5E-1	-321° F.	BCuP-4		21200
3D5E-2	-321° F.	BCuP-4		19900
			Av.	21400
3D6D-1	-321° F.	BCuP-2		17900
3D6D-2	-321° F.	BCuP-2		18800
3D6E-1	-321° F.	BCuP-2		17900
3D6E-2	-321° F.	BCuP-2		17000
			Av.	17900

*Considerable Porosity - not included in average.

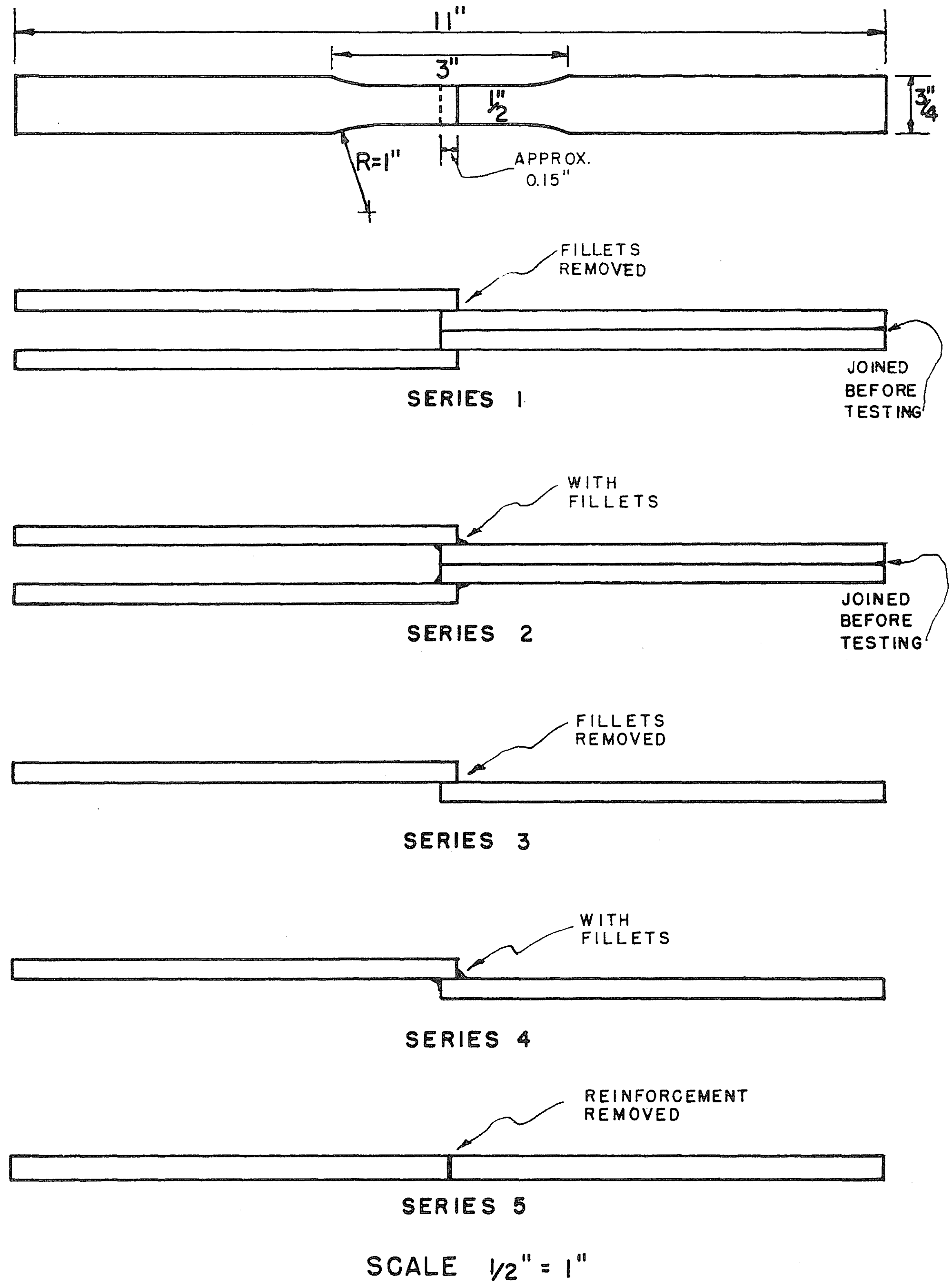

FIG. 1 DETAILS OF BRAZED JOINTS

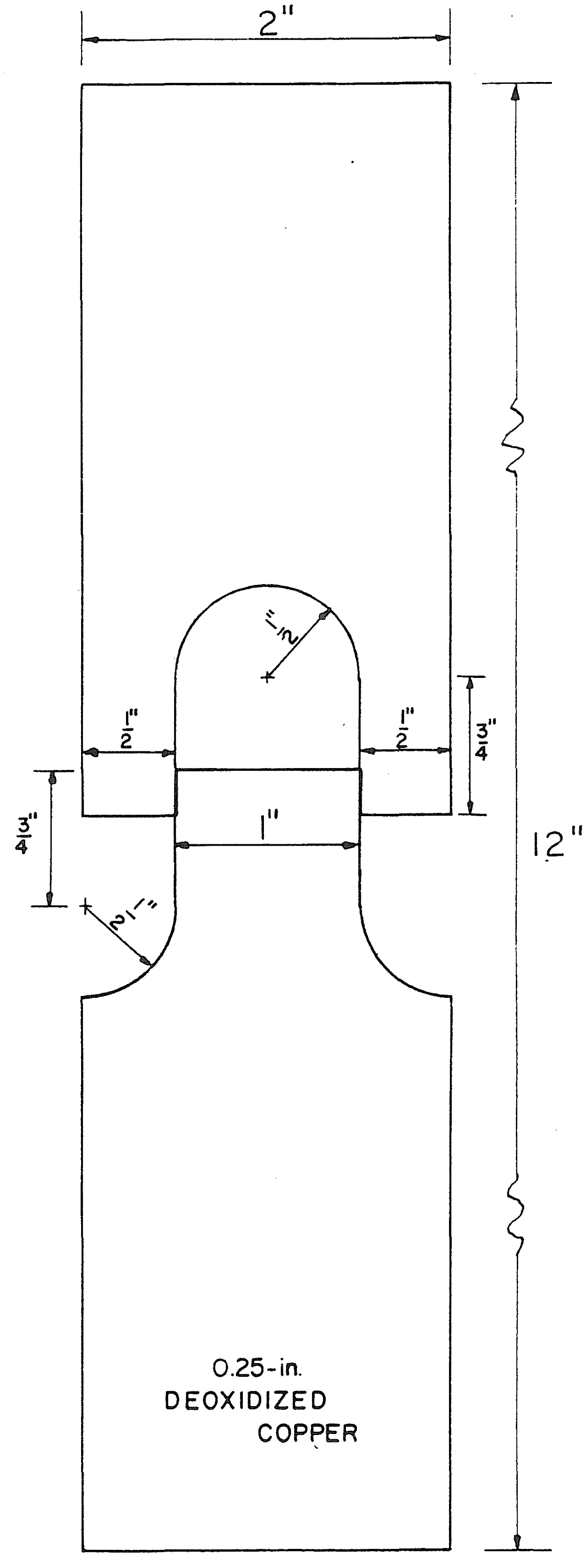

FIG. 2 DETAILS OF GROUP II PRELIMINARY SPECIMENS

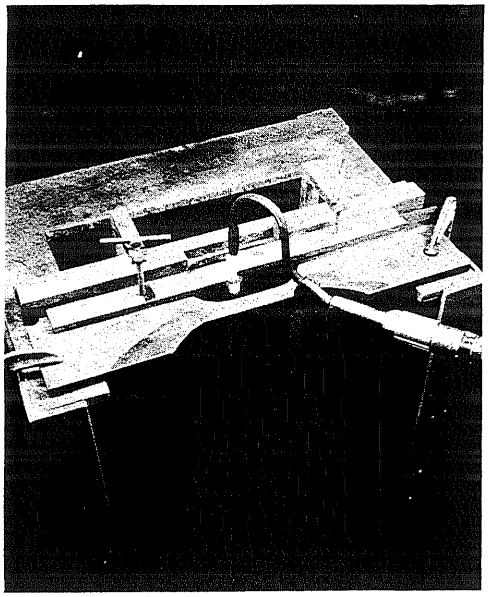

FIG. 3 FIXTURE AND TORCH FOR BRAZING TEST SPECIMENS

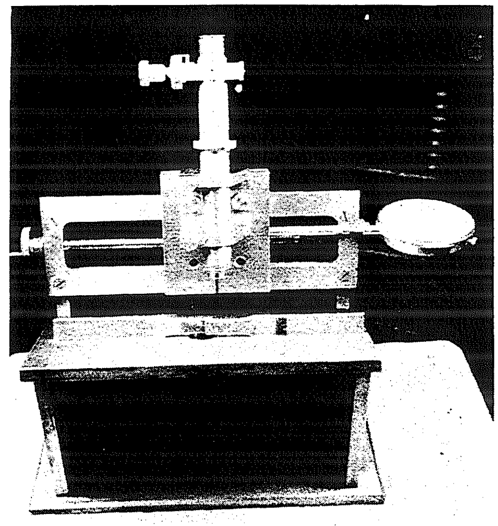

FIG. 4 EQUIPMENT USED TO MEASURE THE LENGTH OF LAP

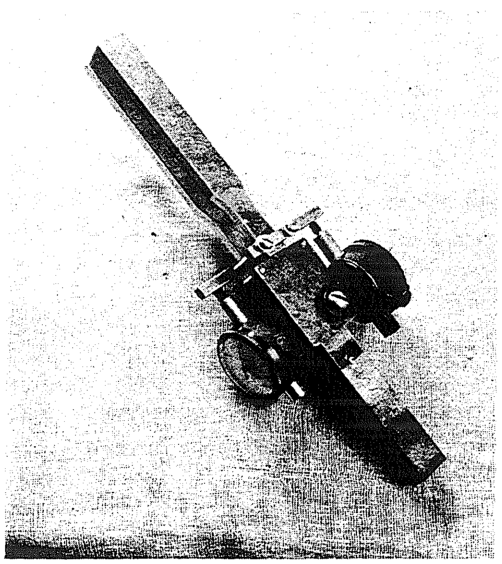

FIG. 5 DOUBLE LAP-JOINT SPECIMEN WITH DIALS MOUNTED

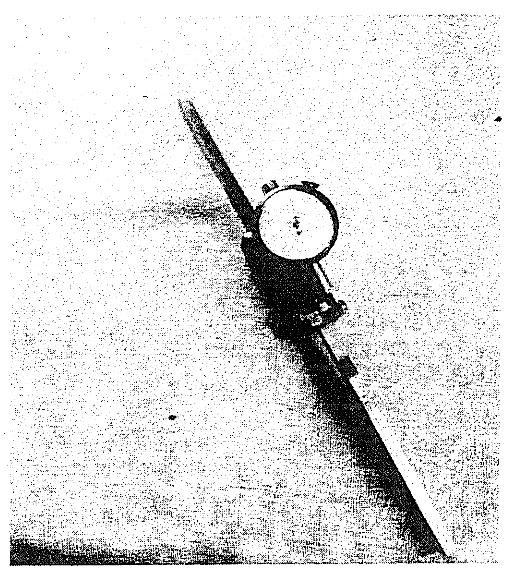

FIG. 6 SINGLE LAP-JOINT SPECIMEN WITH DIAL MOUNTED

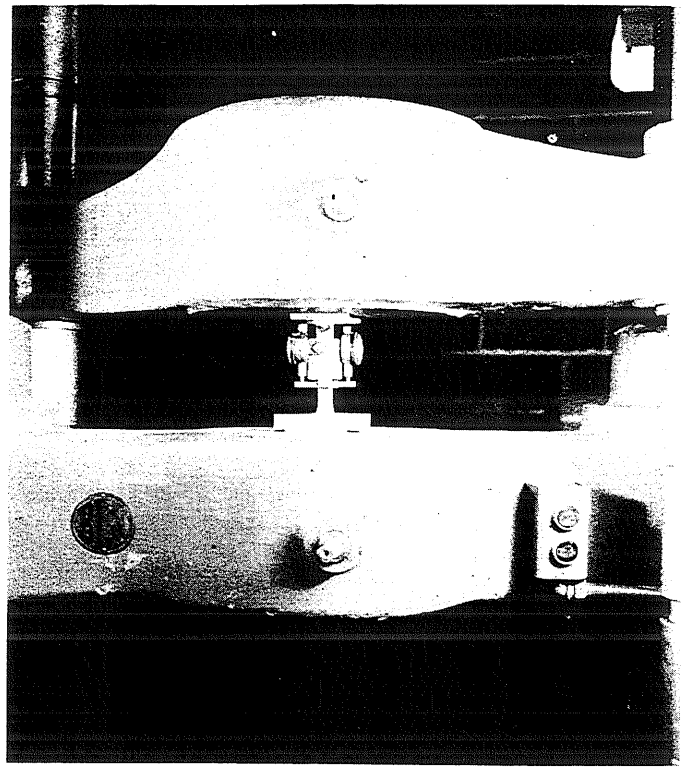

FIG. 7 SPECIMEN IN POSITION IN TESTING MACHINE

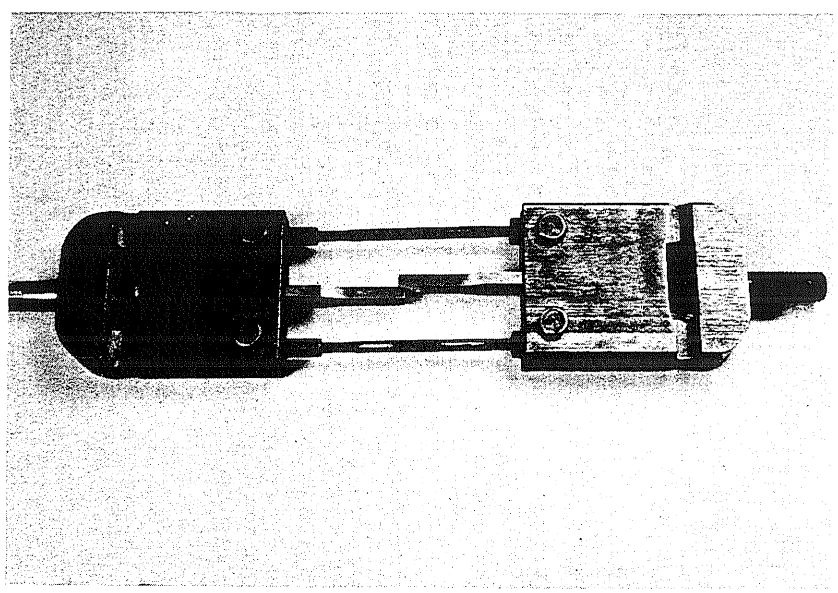

FIG. 8 PULL HEAD ASSEMBLY FOR HIGH AND LOW TEMPERATURE TESTS

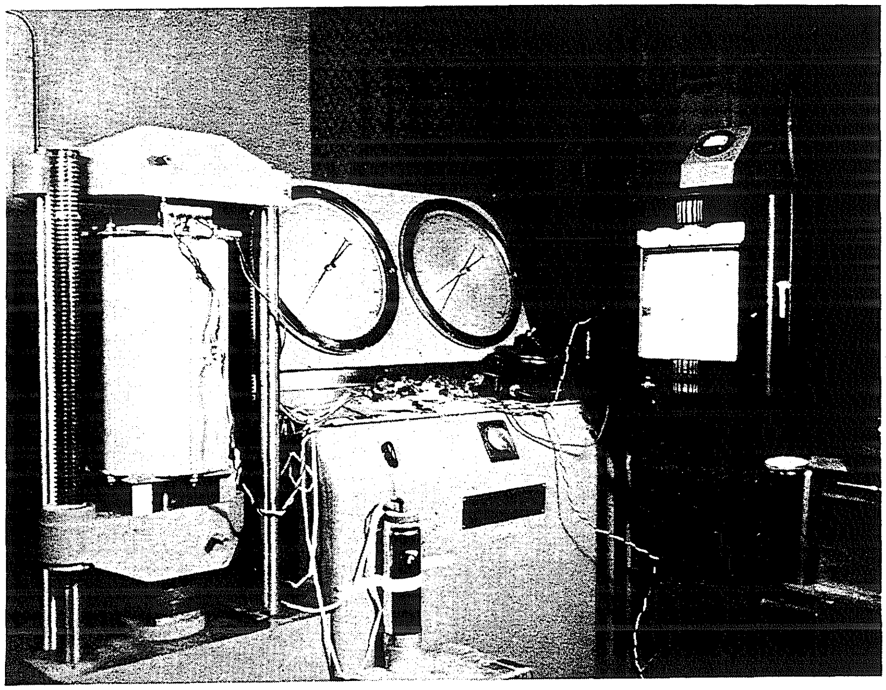

FIG. 9 APPARATUS FOR TESTS AT +400° F.

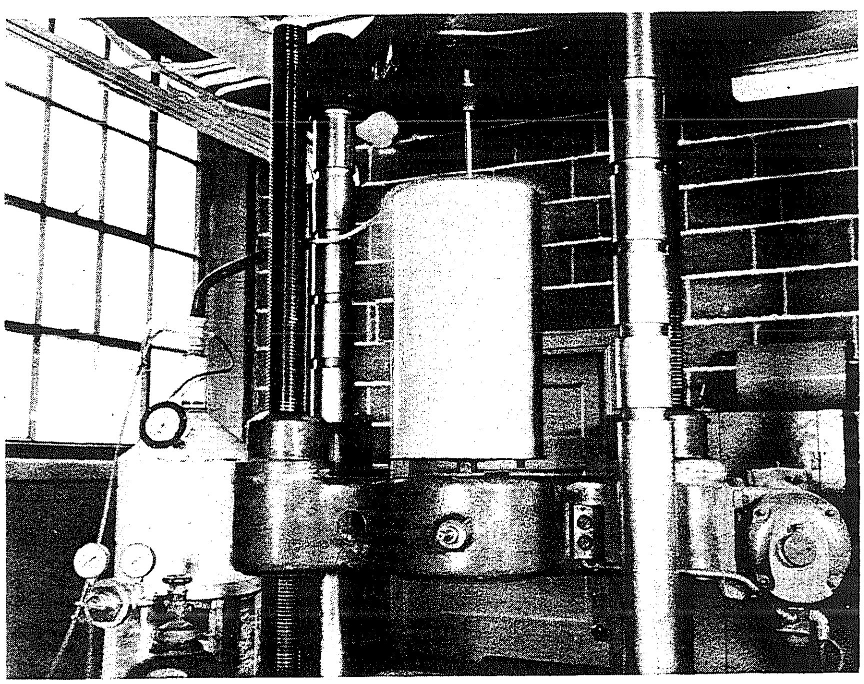

FIG. 10 APPARATUS FOR TESTS AT -321° F.

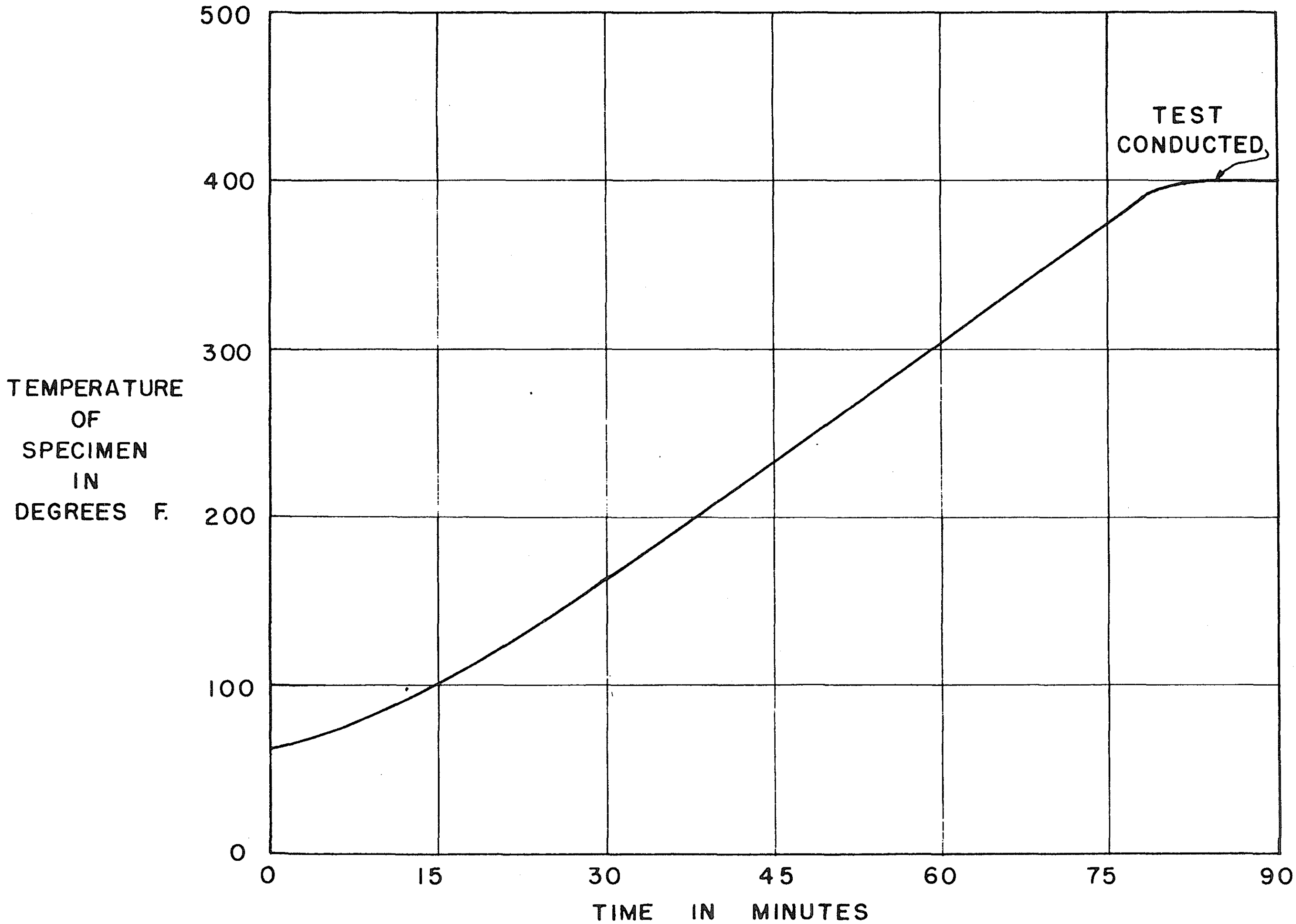

FIG. 11 TYPICAL TIME-TEMPERATURE CURVE FOR A SPECIMEN TESTED AT +400° F.

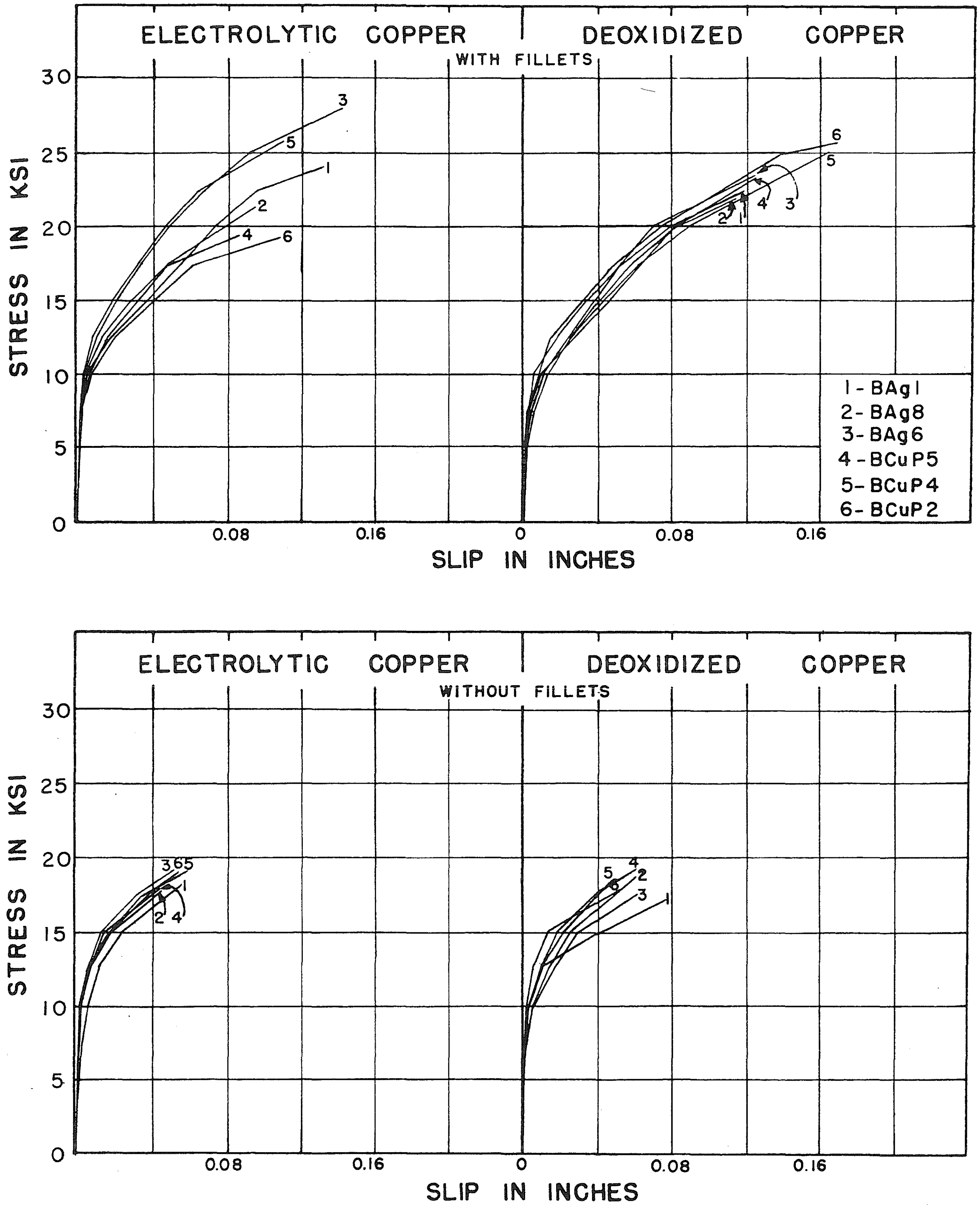

FIG. 12 STRESS-SLIP CURVES FOR DOUBLE SPECIMENS

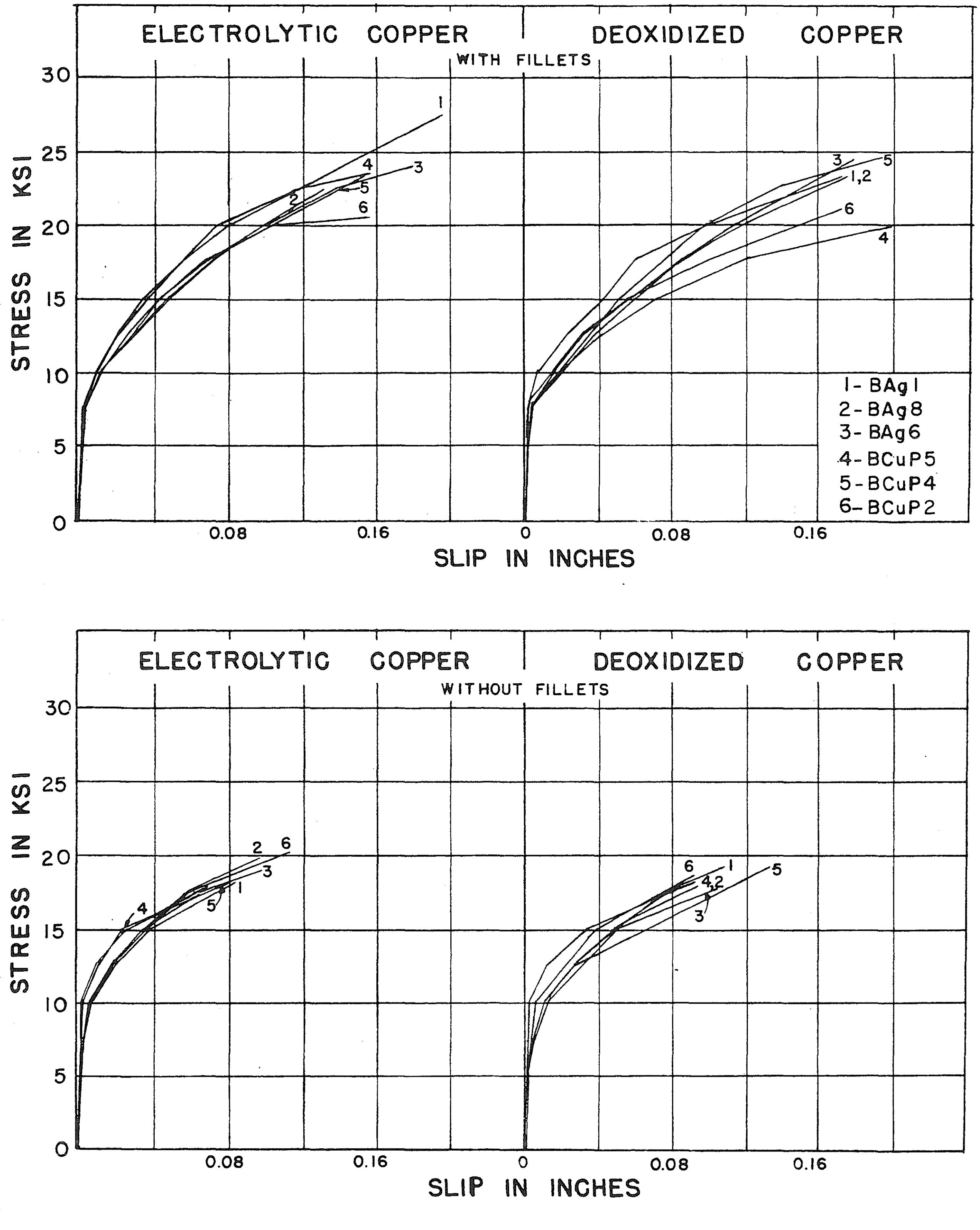

FIG. 13 STRESS-SLIP CURVES FOR SINGLE SPECIMENS

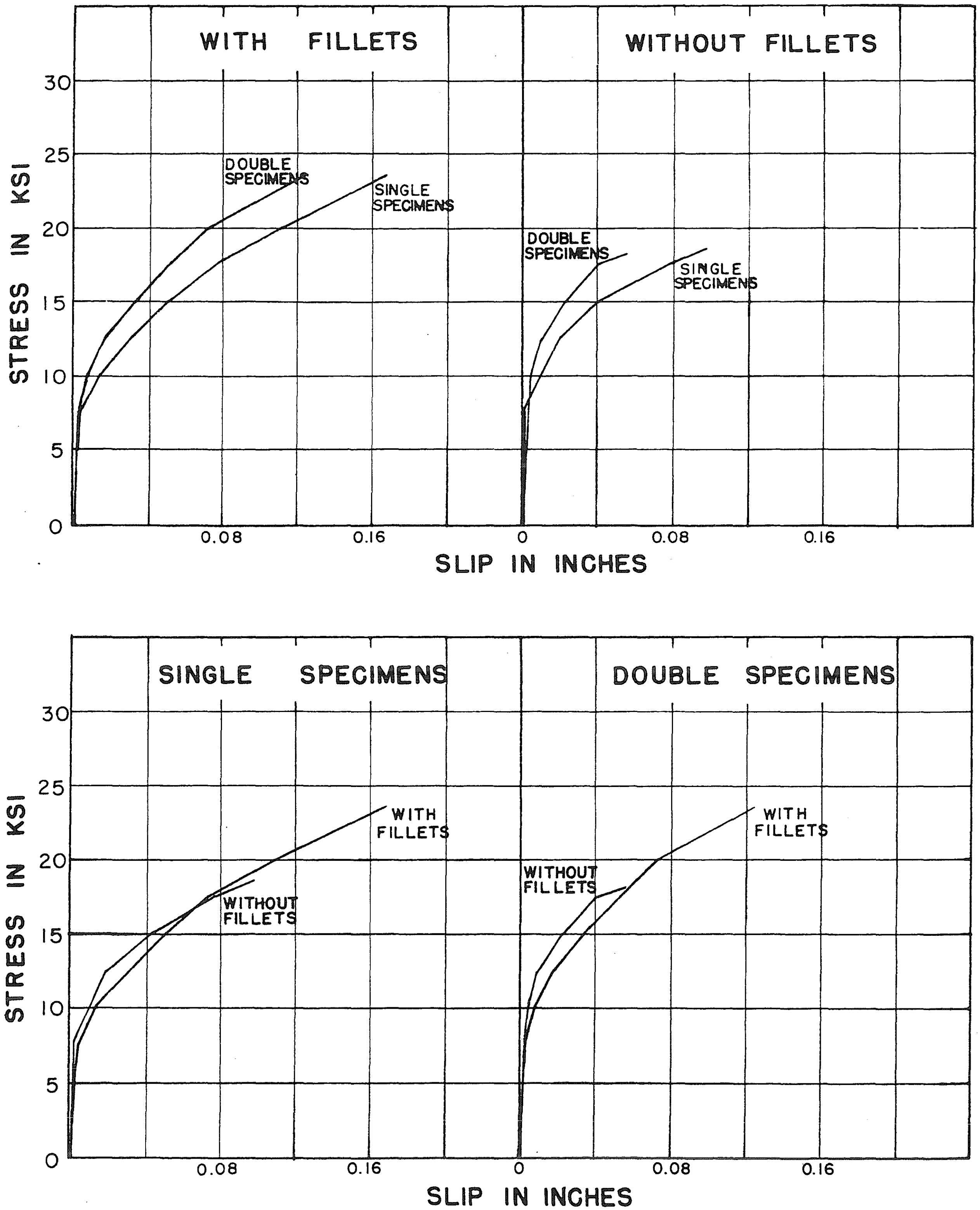

FIG. 14 THE EFFECT OF JOINT TYPE AND FILLETS ON STRESS-SLIP RELATIONSHIPS

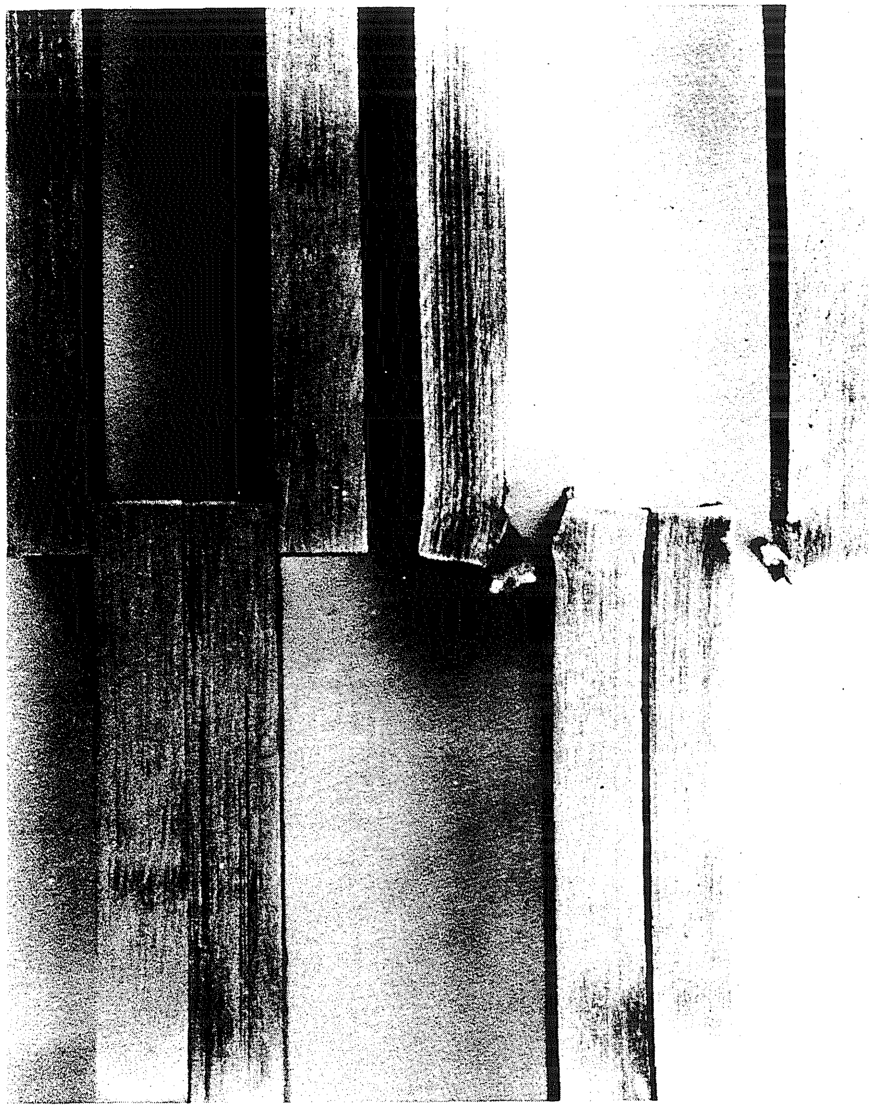

FIG. 15 DOUBLE LAP-JOINT SPECIMEN OF ELECTROLYTIC COPPER

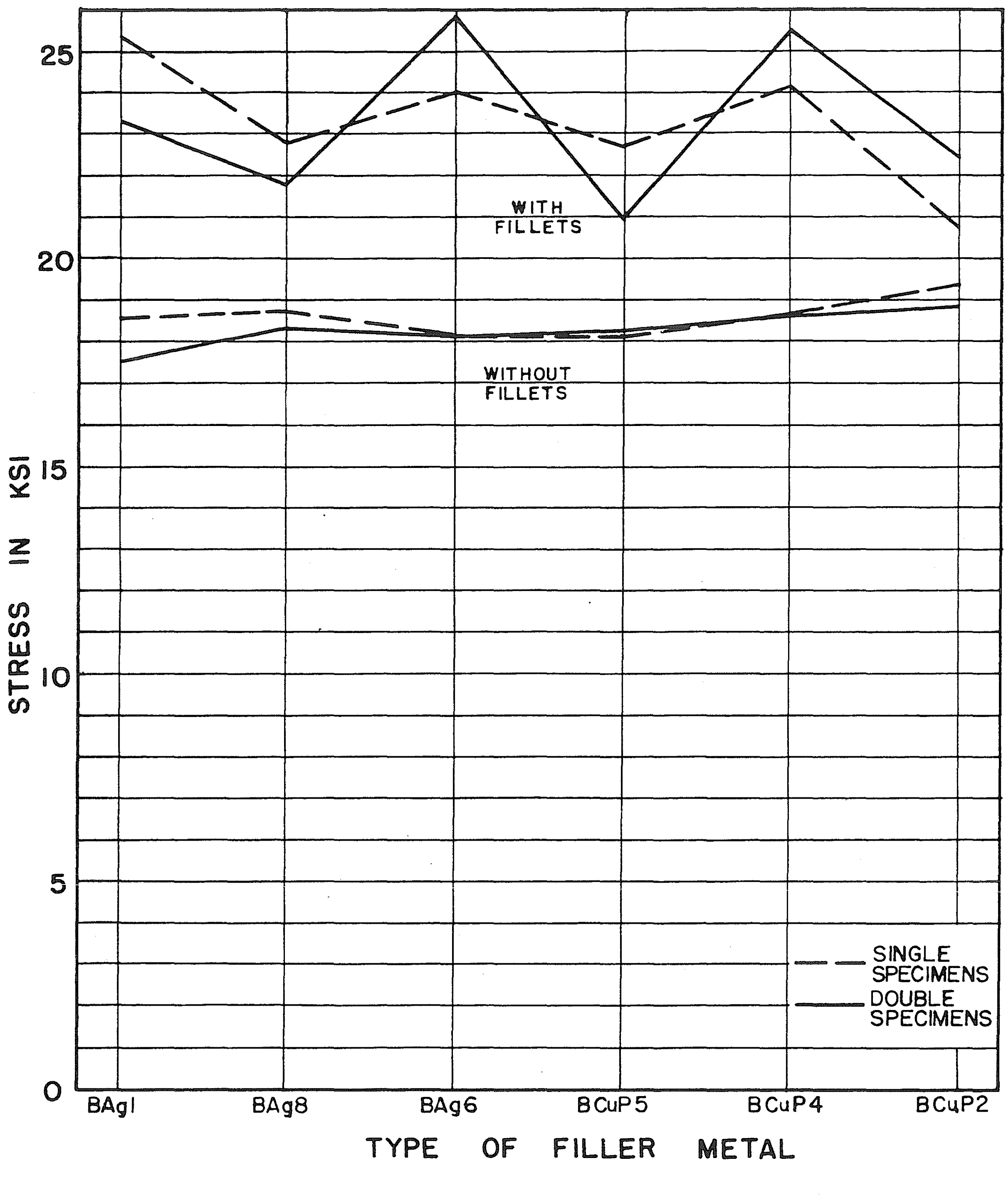

FIG. 16 COMPARISON OF AVERAGE ULTIMATE STRENGTH AND TYPE OF FILLER METAL FOR VARIOUS TYPES OF JOINTS

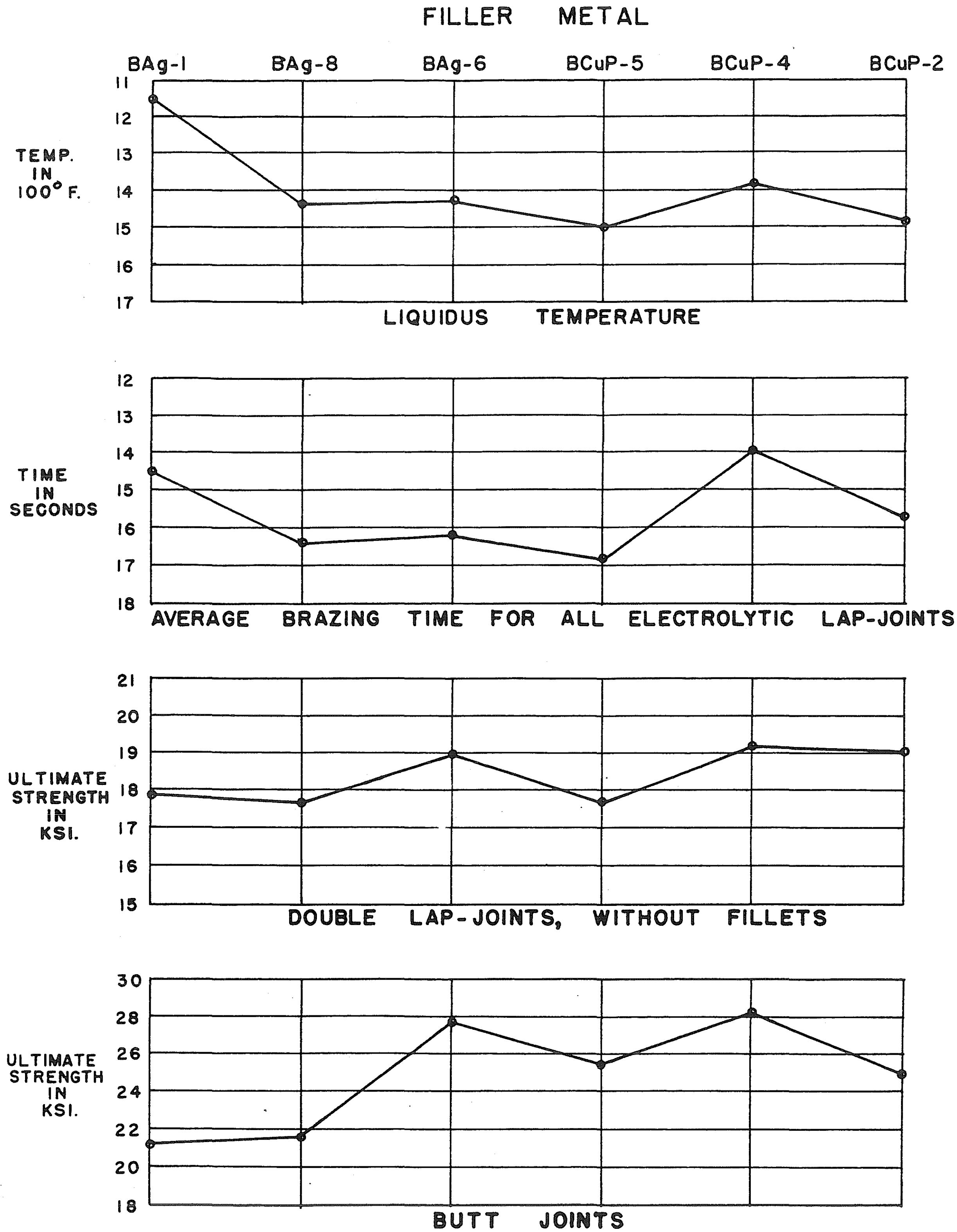

FIG. 17 VARIATION IN LIQUIDUS TEMPERATURE, BRAZING TIME AND STRENGTH OF BRAZED JOINTS OF ELECTROLYTIC COPPER

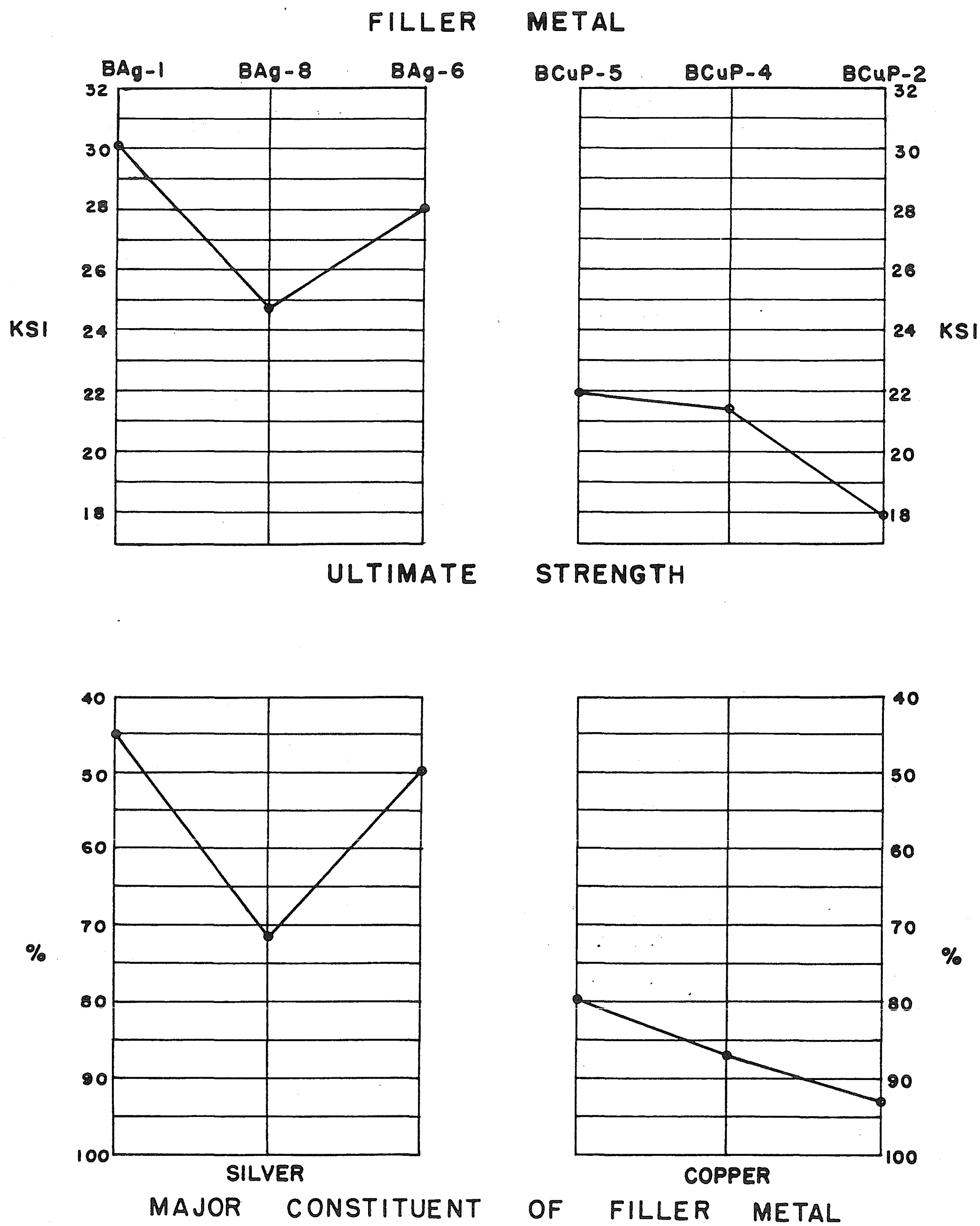

FIG. 18 VARIATION OF ULTIMATE STRENGTH WITH CHEMICAL COMPOSITION. TESTS AT -321° F.